

Lean Limit Extension through Rotating Arc Spark Plugs (RASP) and Adaptive Controls

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Current ORNL ARES Projects

- **Adaptive Control of Combustion Instabilities** – stabilize combustion near lean limit
- **Rotating Arc Spark Plug** – novel plug to extend lean limit
- **Spark Plug Erosion & Failure** – measure plug erosion & ignitibility
- **NG Emissions Characterization** – measurement of regulated & unregulated emissions
- **NOx Sensor Development** – develop new NOx and ammonia sensors for improved emissions control
- **NG Lean Aftertreatment** – develop regenerative & passive emissions control options for lean NG engines

Project Overview

Goals

- Extend the effective lean limit.
- Improve efficiency & NOx emissions.
- Improve robustness of ultra lean burn operation.
- Reduce operation & maintenance costs with novel spark plug.

Tasks

- **Adaptive Control** – reduce instability to extend lean combustion limit.
- **Rotating Arc Spark Plug** – novel design to improve ignitability and spark-to-spark consistency.

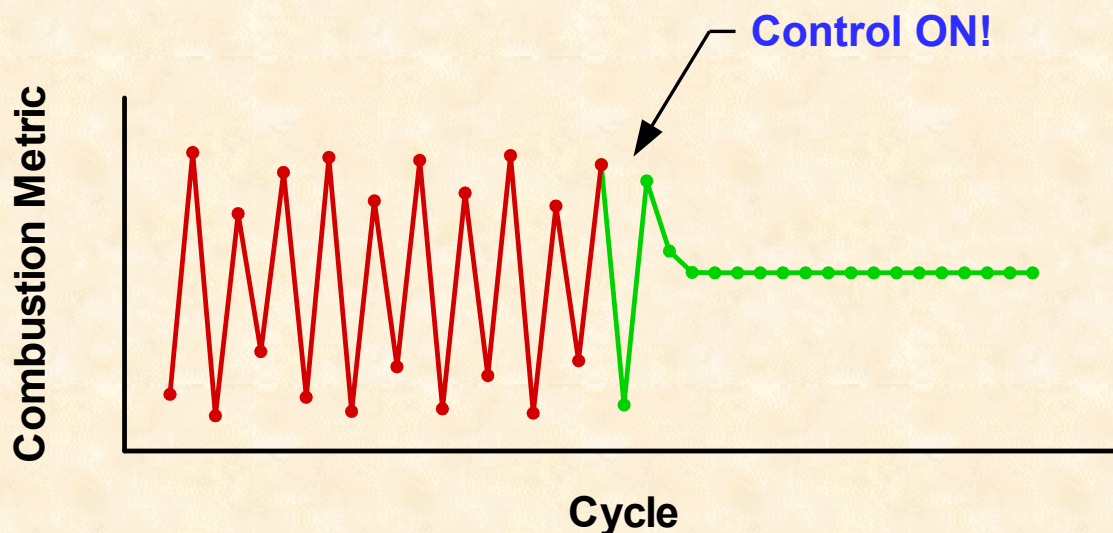
Experimental Platform

- NG Kohler Command 25
- Available in small gen-set
- 3600 rpm
- Port-fuel injected



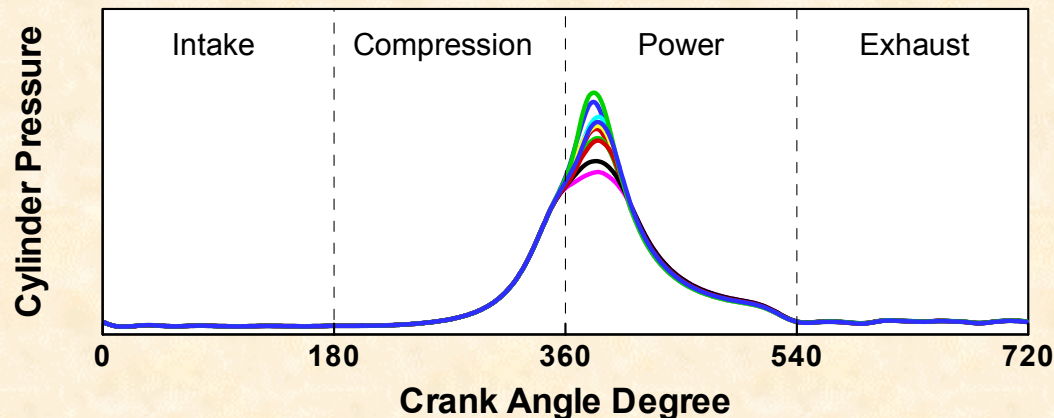
- In-Cylinder pressure measurements
- Advanced control system
- Emissions measurements

Adaptive Control of Cyclic Dispersion In a Lean Burn NG Engine



Why is adaptive control important?

- Cyclic dispersion **INCREASES** near the lean limit.
- Residual fuel causes increases in cycle-to-cycle variations under lean conditions.
- Patterns complicated by parametric noise.
- Fluctuations can be minimized with proper control strategy.



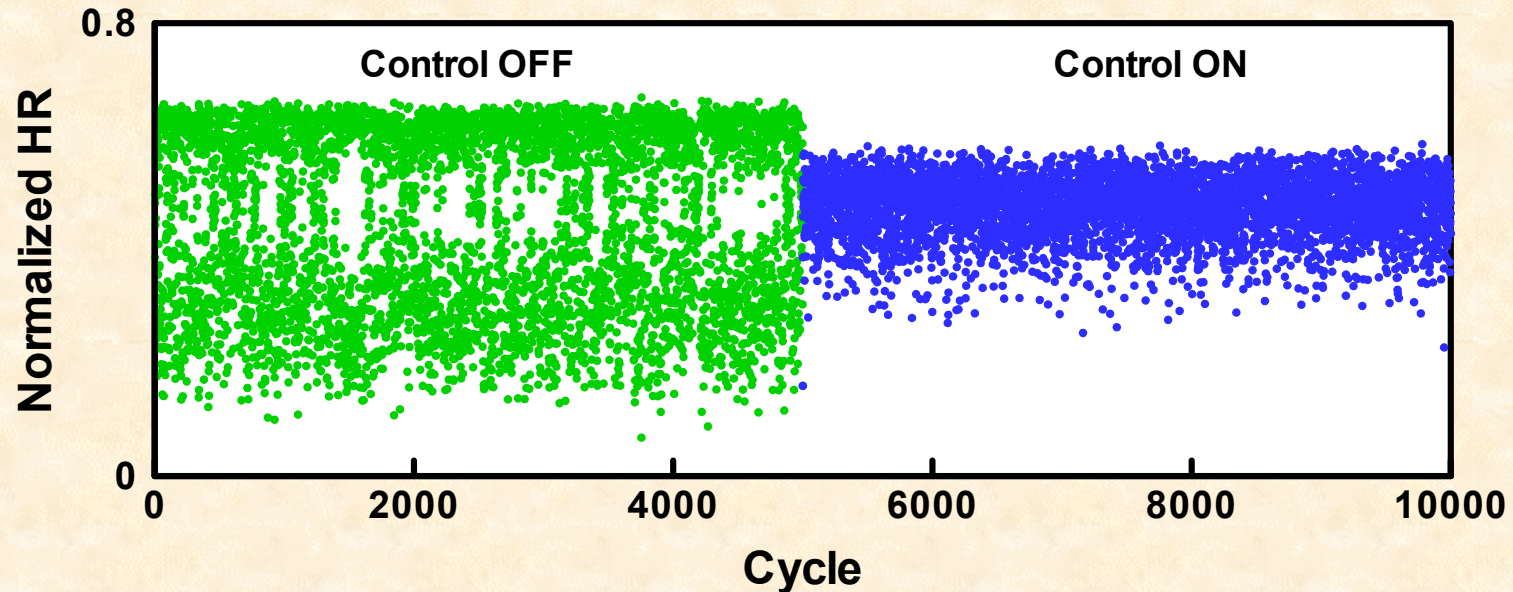
Approach

- **Develop and refine control algorithms on SI engine model.**
- **Develop hardware for evaluating control algorithms on an actual engine.**
- **Demonstrate benefits of adaptive control on Kohler NG engine.**
- **Collaborate with universities and industry to scale technology to large NG engines.**
- **Migrate to other ARES-sized engines.**

Technical Accomplishments

- Development of promising control strategies.
- Acquisition of control hardware capable of high-speed combustion evaluation and cycle-by-cycle perturbations to control parameters.
- Significant progress towards stabilizing lean combustion instabilities on an actual engine (Kohler).
- Preliminary discussions with Colorado State University and industry to scale technology to large NG engines.
- Interacting with ARES team to develop plan for technology transfer.

Control algorithms initially developed on model

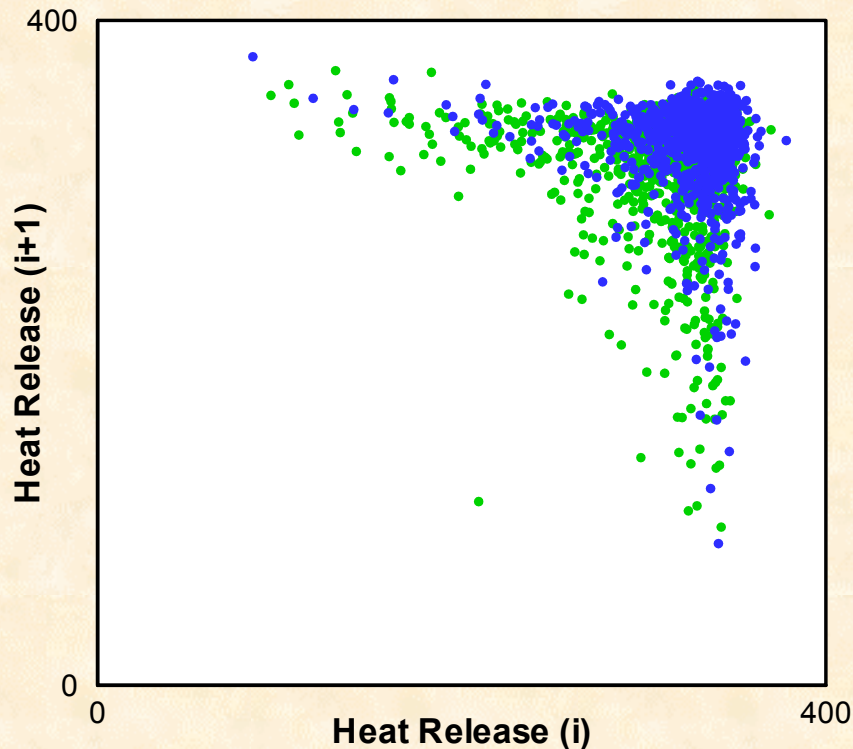


- Control decreases misfires and partial burns.
- Based on known history (look-up maps).
- No net increase in fuel useage.

Rapid Development System (RDS) will be used to implement and evaluate control schemes

- Full-pass engine control.
 - injection parameters, ignition, throttle, etc.
 - MATLAB/Simulink based interface.
- Crank-angle resolved in-cylinder pressure.
- Cycle-resolved combustion characterization.
 - IMEP, heat release, etc.
- Cycle-by-cycle control perturbations.

Control algorithms implemented on Kohler engine for proof-of-principle



Control OFF (COV 13%)

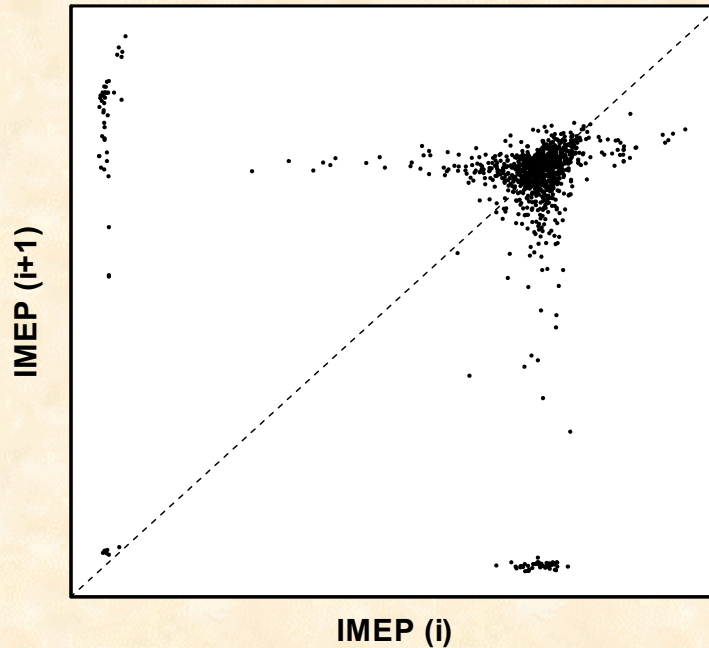
Control ON (COV 9%)

**Moderate reduction in
cyclic dispersion with no
net increase in fuel usage.**

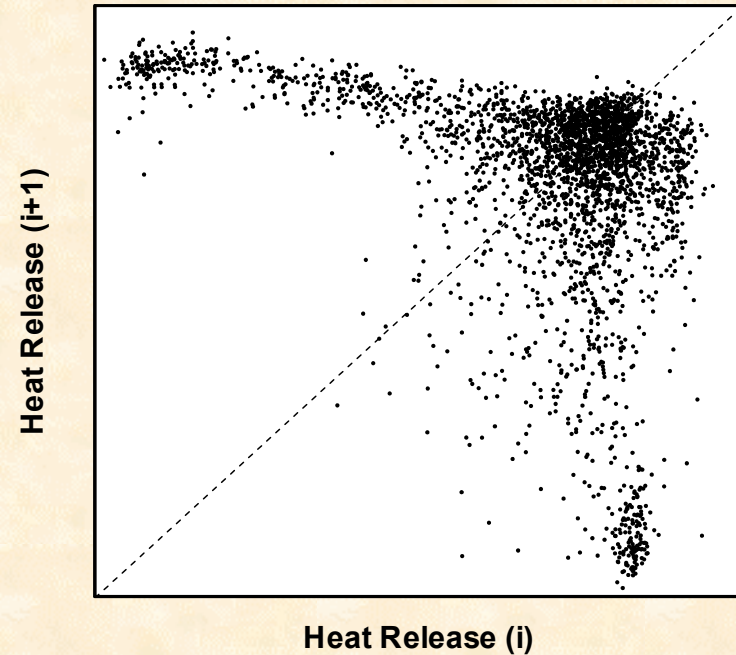
**** Results as of October 2003**

Collaboration with *Colorado State University* to explore instabilities in large engines

Cooper-Bessemer GMV 4TF
(CSU, 2-stroke, 36.0 cm bore)



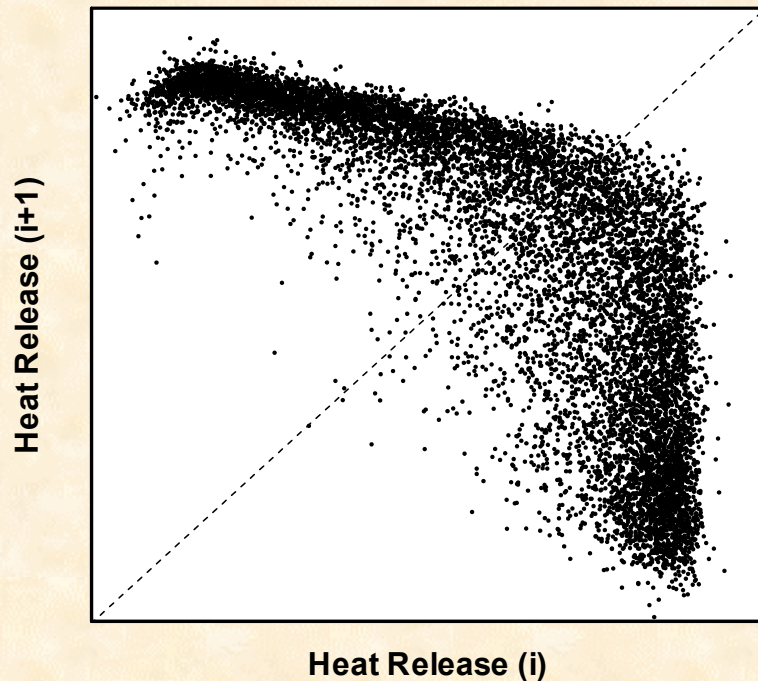
Kohler Command 25
(ORNL, 4-stroke, 8.3 cm bore)



Development of instabilities is fundamentally the same for both engines.

High EGR with stoichiometric fueling exhibits similar instabilities

Ford Zetec (gasoline)



- Benefits of 3-way catalyst realized with stoichiometric fueling.
- Control algorithms developed for lean instabilities are applicable to high EGR operation.

All SI engines examined so far exhibit similar instabilities.

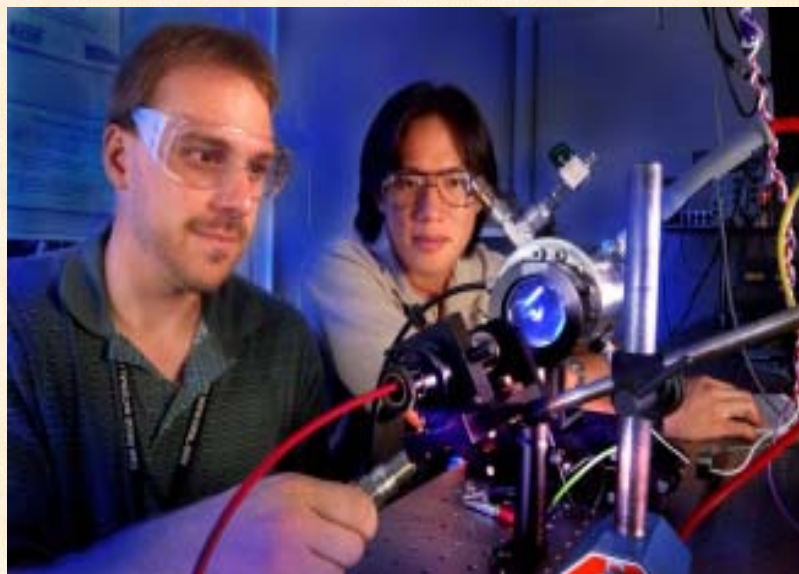
Milestones

- **Develop nonlinear control system hardware (June 2003)**
 - Milestone was met on time! Hardware is operational and capable of evaluating adaptive high-speed algorithms.
- **Demonstrate nonlinear control under lean burn conditions (December 2003)**
 - On track to meet on time! Initial results are promising (shown).
- **Identify strategies and possible collaborations relevant to adapting control to large natural gas-engines (June 2004)**
 - Preliminary discussions have taken place with Colorado State University and industry.

Technical Risks, Barriers, and Successes

- **Hardware capable of combustion evaluation and control.**
 - Recent hardware acquisition has made implementation of control algorithms possible.
- **Large engine (ARES) combustion dynamics similar to those observed on small engine (ORNL).**
 - CSU data and other ORNL experiences indicates that instabilities are fundamentally the same.
- **Control algorithms capable of short-term prediction in presence of high levels of noise.**
 - Model and Kohler engine experiments indicate control possible.
- **Learning engine behavior for control implementation.**
 - History assumed known and improved with operation.

Rotating Arc Spark Plug (RASP)



RASP Concept

- Axial magnetic field imposed on radial-gap plug causes radial arc to rotate circumferentially by the Lorentz force.
- Degree of rotation depends on magnetic field strength, current amplitude, and spark duration.
- High temperature permanent magnets used to eliminate magnet degradation .



Rotating Arc Spark Plug (RASP) Benefits

- Reduce cycle-to-cycle combustion variations by improving spark-to-spark consistency.
- Improve ignitability of lean mixtures by increased arc volume and higher plasma temperature.
- Increase spark plug life (decrease maintenance) by decreasing plug erosion due to multiple arc sites.
- Reduce manufacturing variability and costs .

Approach

- **Bench Development & Evaluation**
 - Stainless steel version evaluated at 200 psig in magnetic and non-magnetic medias.
 - Optical spectroscopy, arc rotation speed, arc current and voltage measurements.
- **Engine Development & Evaluation**
 - Kohler NG engine with aluminum head.
 - Multiple iterations related to head material, arc gap, thermal management, and magnet location.
- **Migrate to more conventional engine (with ferromagnetic head).**

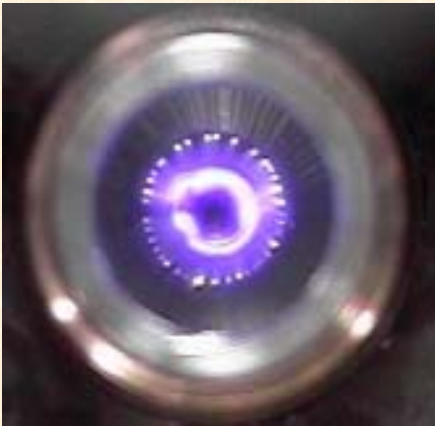


Technical Accomplishments

- Multiple RASP configurations have been designed, fabricated, and evaluated on the bench and engine.
- Improved thermal management to overcome degradation of magnetic field caused by exposure to high temperatures.
- Latest design is most promising and prototype is currently being manufactured by Champion.
- Arc rotation reduced but not eliminated in engine head of magnetic material. RASP benefits may still apply to cast iron heads.

Effect of magnetic field on arc has been evaluated

**Maximum
magnetic field**



**Intermediate
magnetic field**



**Minimal
magnetic field**



**Arc with no
magnetic field**



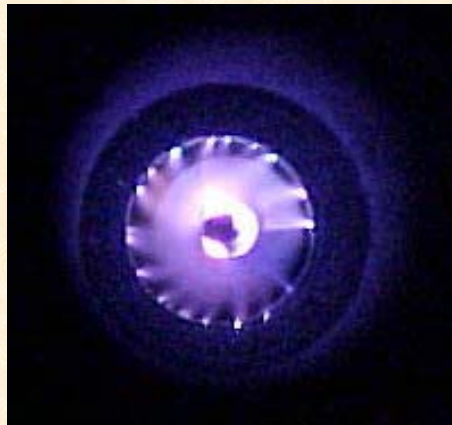
Typical arc rotation speed ranges from 80 to 400 revolutions per second.

Arc rotation in different materials to evaluate application in magnetic engine heads

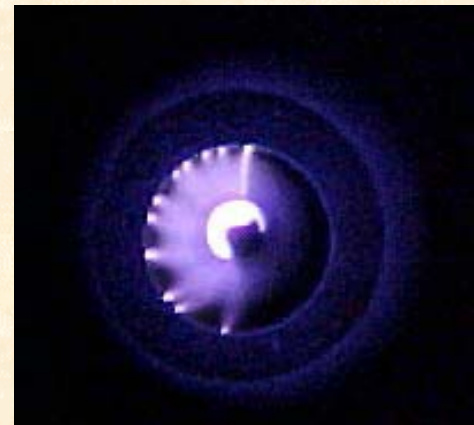
Non-magnetic
brass housing



Non-magnetic
stainless steel
housing



Magnetic
mild steel
housing



Arc rotation is reduced but not eliminated in an engine head of magnetic material. RASP benefits may still apply to cast iron heads.

Collaborations

- Teamed with Champion (Federal Mogul Corp) for design and fabrication of prototype RASP.
- Champion manufactured and supplied over 50 stainless steel plugs with 4 different gaps.
- Electron Energy Corporation supplied high-temperature Sm-Co permanent magnets.
- Interacting with ARES team.



Milestones

- **Evaluate RASP on an engine under lean conditions (September 2003)**
 - Not fully met. Turn-around on prototype iterations longer than expected. Plugs expected January 2004.
 - Several designs have been evaluated and many issues have been resolved.
 - Most promising iteration currently being designed/fabricated.
- **Demonstrate and evaluate RASP on conventional engine under lean conditions (September 2004)**
 - Preliminary experiments to quantify RASP behavior in magnetic materials similar to conventional engine heads.
 - Arc rotation is reduced but not eliminated – still has benefits with conventional engine head materials!

Technical Risks, Barriers, and Successes

- **Permanent magnet (arc rotation) may be influenced by combustion temperatures.**
 - Initial experiments revealed significant magnet degradation due to high engine temperature.
 - Combination of good thermal management and high-temperature magnets in new design results in no measurable magnet degradation.
- **Arc rotation influenced by engine head material (e.g., steel).**
 - Experiments indicate arc rotation is reduced but certainly not eliminated.
- **Design must compromise on magnetic field and arc location to maximize ignitability.**
 - Iterations in design still in progress. Most promising design is currently being fabricated for ORNL by Champion.

Overall Project Summary 1/2

- **Relevance** – Significant progress toward ARES goals of higher efficiency, lower NOx emissions, & decreased maintenance costs.
- **Approach** – Simulation (bench, model) and engine (real world) evaluation development.
- **Accomplishments** – Program is progressing and is well positioned for important near-term milestones.
 - Development and implementation of promising control strategies on an actual engine.
 - Multiple RASP design iterations successfully overcame several perceived risks/barriers. Most promising RASP iteration is being fabricated and is expected in January 2004.

Overall Project Summary 2/2

- **Future** – Solid plans in place for FY2004 and beyond.
 - Demonstrate adaptive engine control and benefits associated with lean limit extension. Transfer control system to large natural gas engines.
 - Evaluate RASP under lean conditions and adapt to more conventional natural gas engine.
- **Collaborations**
 - CSU and industry collaborations being formed to evaluate and scale control technology to large NG engines.
 - Champion is involved in the fabrication of prototype RASPs.
 - Interacting with ARES team on a regular basis.

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